Abstract – Nowadays the evolution of electrical engineering achieved a successful expansion in the area of fault tolerant electrical machines. To achieve fault tolerance researchers tried to design various geometries and different electrical drives. When new designers are intended to be performed the knowledge of the actual state of the work is imputuously needed. The paper summarizes the most important information on these topics. Both fault tolerant machine and drive structure were taken into accounts. In the paper also a new idea for a fault tolerant switched reluctance machine having a special winding is presented. The future tasks to be performed are also mentioned in the paper.

Keywords: Fault tolerance, fault tolerant electrical machines and drives.

I. INTRODUCTION

By definition, fault tolerance of a system is its ability to continue its work even if a failure occurs. The fault tolerant concept emerged for the first time in information technology. It meant an increased level of continuous operation of computer equipment. Later more and more fault tolerant equipments were connected together in order to form a fault-tolerant system [1, 2]. The result was an operational unit having certain fault tolerant level, as a sum of the safety levels of each equipment of the system. A system is reliable when it is capable of operating without material error, fault or failure during a specified period in a specified environment. From another point of view a system is dependable if it is available, reliable, safe, and secure [3]. An electromechanical system is driven by a unit composed of the power converter and of the electrical machine. Both must be fault tolerant. The electrical machine's fault tolerance design has to be in a manner to assure unchanged, as possible, output parameters also in case of fault occurrence. To be able to achieve an optimum solution for a fault tolerant machine, all the advantages and drawbacks have to be taken into account for the new structure. From the inverter's point of view, as the evolution of the power electronics hit an exponential slope, the separation of command and control of each phase will set the required fault tolerance level [4].

Critical electrical machines and drives systems used in diverse fields like aerospace, defense, medical, nuclear power plants, etc. require both special, fault tolerant motor and converter topologies. For example for electric drives used in propulsion applications faults can be critical, since an uncontrolled output torque may have an adverse impact on the vehicle stability, which ultimately can risk the passenger safety. All theses mentioned above have stimulated the researches in the field of fault-tolerant electrical machines and drives [5].

In our days due to the recent technological advances and developments in the area of power electronics and motor control the fault tolerant electrical machine and drive concept reached a level where it begun to be feasible to be used widely in practice.

There are a lot of elements in an electromechanical system that can be changed to reach for the summits of fault tolerance concept. Hence, modifications in the machine’s topology proved to be the trickiest method for improvement.

It was proved that changing a small parameter in a machine’s geometry, raises huge amount of output changes. As a second step the winding can be modified. Diverse way to design the winding, different placement or couplings between the coils were proposed. Using great number of phases became a widely used design method in solving fault tolerant problems. The main idea was to substitute the faulted phase’s contribution by the healthy remaining ones.

II. GEOMETRY APPROACH FOR FAULT TOLERANCE

Electrical machine’s geometries can be changed to obtain fault tolerant designs. Depending on the construction and type of the machine, several improvements can be applied. Usually when a custom machine is designed, there are some basic criteria that the machine has to fulfill (minimum losses, mass, etc.). These criteria must be also taken into account when designing fault tolerant machines. Hence, a possible solution should be the use unsymmetrical stator pole teeth. Its usefulness was proved in [5]. By a small change in the stator structure the winding losses were reduced by near 44%, which is a consistent improvement in the machine's design.

Another solution in the case of multi-phase machines should be to increase significantly the number of teeth (see Fig. 1.) [4].
This increased number of teeth will assure low torque ripples also in case of different faults. As much the number of teeth is increased, the torque ripple will be more diminished.

Other designers proposed models of fault tolerant topologies with a lower number of teeth, a shown in Fig. 2. This of course the simple magnetic circuit structure was completed by a more complex winding: high number of phases and a complex winding plan. This solution also requires a complicated drive unit [7]. Fractional slot winding configurations allow the machine to well operate also in faulty conditions. However, the MMF harmonics in this case are consistent, and this might cause an unbalanced saturation and an unbearable torque ripple.

Fault tolerant topologies are also applicable for embedded permanent magnet electrical machines designs. The magnets assure a part of the magnetic flux needed for the force generation, even when a part of the winding is damaged.

Changes to be performed on the already existing designs of electrical machines in order to achieve fault tolerance is quite difficult.

To optimize permanent magnet fault tolerant synchronous machines, in [8] armature coils are placed in pairs of slots. The walls of the slots are parallel to themselves and to the wall of the other slot of the same slot pair. Between two pair poles, there is a spacer tooth (see Fig. 3). These are narrower than the main teeth to provide greater magnetic flux linkage between them and thus increasing the EMF within the corresponding coil.

For a switched reluctance machine, as the rotor is a passive one, this solution cannot be applied to achieve a fault tolerant variant. The solution is to make the rotor active by placing a winding in closed loop around each rotor pole (as shown in Fig. 4).

This will assure a reaction for the stator to rotor flux, resulting in a rotor to stator flux. Practically, this emphasizes a magnet; hence, the rotor will generate the force needed for passing over a pole having damaged winding [9].

III. WINDING APPROACH FOR FAULT TOLERANCE

As it was stated out before another possibility for achieving fault tolerant electrical machines is by changing the winding arrangement. Usually windings for each machine have their typical well-known arrangements.

A first possibility is to assure an independency between the phase windings in the machine.
Usually high number of coils and a high number of phases are applied in order to reduce the effects of winding damages. Fractional slot concentrated arrangements in a machine with permanent magnets embedded in the rotor assure higher torque density, negligible cogging torque and also small torque ripple [10].

The machine described in [10] had 30 slots and 28 poles of magnet. So in the 30 slots, the 5 phases gave 6 slot throw, practically giving a complex winding system, and due to this a complex drive, too (Fig. 5).

![Image](image-url)

**Fig. 5. A fault tolerant brushless DC machine variant**

An other idea should be dubling the stator poles. This demands also for doubling the number of phases of the winding system. This can be done by having multiple stator poles defining multiple stator slots, and at least two sets of stator windings, wound on the stator poles, so this way the end windings are shorter, and they are not overlapping. One set of windings can be placed in the upper half of the stator, and the second one in the lower one [11]. Connections between coils are set regarding the electrical drive that feed and command the machine.

In case of winding short circuits, the fault must be isolated and masked by the inverter. For this, independency between same phase windings on different poles must be considered as leading concept. The task is to find the optimal solution for connecting the phase windings to the inverter, and defining the best winding type. In [12] a comparative study is given regarding two machines, with concentrated and distributed windings. It was proved that optimal for fault tolerant variants are the concentrated winding type.

IV. FAULT TOLERANT DRIVE SYSTEMS

The machine’s drive is responsible for commanding and feeding correctly the phase windings, and making sure, using feedback loops that the output demand is achieved [11]. If fault tolerant concept is implemented in an ordinary drive, changes by means of topology are needed.

Building intelligent equipments that can detect a fault, and can mask and compensate it, defines fault tolerant concept for drives. This will require the drive to reconfigure its working skills and operating modes. The result will be in means of output machine parameters that have to be kept in given values.

For three-phased AC machines, six switches, two for each phase, are used in the drive. In case of one phase fault, the rest of five switches can reconfigure by command in order to play entire the role of the faulted phase, too. A recomputation of firing angles is required to ensure the masking of the faulted phase. This way the machine can have mechanical output with respect to the demand.

An other idea is to have a fourth command branch in standby (Fig. 6). When the fault appears in the machine, the standby branch becomes active [15].

![Image](image-url)

**Fig. 6. Forth branch standby branch scheme**

In the case of AC drives for AC machines other opportunities exist to improve the intelligence of the drive to face the fault.

For example in a synchronous machine the drive must deliver, in normal circumstances, three-phased currents for the phases. If one phase is turned off due to a fault of a power device, or a winding open circuit, the same fundamental MMF wave form can be obtained by the remaining two phases. Appropriate reference values for the other two phase currents will be necessary to get the same wave form. After turning off one phase the other phase currents are shifted by $\frac{\pi}{3}$ (instead of $2 \frac{\pi}{3}$), and the amplitudes are multiplied by 3. Phase currents transformed to the $ab$ reference frame are not affected, but the homopolar component $i_0$ is no longer equal to zero [16].

The division of a drive in subsystems, each one for command and feed of a single phase can be used to develop fault tolerant topologies. The common element for all the subsystems of a single drive is the main bus bar. This way, the fault in the machine can be tolerated by the reconfigurable property of the drive.

The division can go on and on. There is the possibility to even ensure a different power supply for each sub-drive. In this case, if the machine is also fault tolerant, the drive is reconfigurable and it has each sub-drive feed separately, an extreme high level of tolerance is achieved [17].
V. ACCOMPLISHMENTS IN THE FIELD OF FAULT TOLERANT ELECTRICAL MACHINES

There are electrical machines that allow adding the fault tolerant concept in their operation. The elements that can be modified in the system of an electrical machine are: feeding and control devices, windings, and the magnetic circuit structure. Also there are machines that have a more "rigid" structure to fault tolerance. However, studies included also these machines in attempting to develop machines with new performances and reliable operation. For example, the induction machine has a structure that does not allow many changes. This forced the engineers to concentrate on its electrical drive attached to the machine. The new drive sets an intelligent operating mode combined with a continuous feedback for any sudden change in the machine’s behavior.

Normally, an induction machine has three phases, each of them fed with sinusoidal voltages having a phase delay of $2\pi/3$. In case of a fault, the drive is able to ensure currents in the remaining two phases to cover the missing one's contribution. This intelligent drive uses for driving the motor first, second and third gate logic signals [18].

When considering operation of a machine in fault condition, the thermal aspects must be taken into account, too. As currents in the windings will be higher, the thermal tolerance must allow a non-destructive operation in means of insulation class and cooling. If the fault tolerance is offered only by the drive, without current rise in the phase windings, the insulation class and the cooling system can remain the same [19].

The synchronous machine was approached with a large respect to the fault tolerant concept. Usually the preferred structures are the ones excited by permanent magnets. Practically, no need of an exterior continuous current source, windings, brushes and contact rings, instead of permanent magnets, already assures a sort of fault tolerance. The magnets will always have the same contribution in creating the motion without any extra voltages needed. As the rotor issue is solved, the stator remains the main part that can suffer of faults.

One approach regarding the stator is the changing of winding scheme by having a plurality of stator poles defining a plurality of stator slots, and at least two sets of stator windings wound on the stator poles (Fig. 7). This way the end windings are shorter and they are non-overlapping. One set of windings can be placed in the upper half of the stator and the second one in the lower one [20].

Modifications on the machine structure can help improve the tolerance level. An idea is to insert elements that can help guiding the flux to obtain a symmetrical distribution when fault occurs. These elements are non-magnetic sleeves fixed with respect to the stator parallel with the main rotor axis, using the main winding scheme (Fig. 8). This way a high permeability zone is created for shunting the flux paths of the faulty stator windings. These modifications will allow operation in fault condition, but with lower output power [21].

The problem with this structure is that in the case of fault, the machine is not able to reconfigure the flux path by its own. For this, the machine has to be stopped, locate the fault by an outer operator, and insert the non-magnetic sleeves in the appropriate slots to shunt and redistribute the flux in correct way, from the side of rotor view.

Because the drive of a synchronous machine can provide a good tolerance to defects, there are a lot of possible ideas in building fault tolerant and intelligent drives. The current in the machine is usually controlled by using PWM method, offering a quick feedback, and high precision. Taking advantage from it, there are methods of detecting the fault, with the same speed and the same accuracy. Detection of fault uses an estimation of parameters from the mathematical model of the motor from the input-output data. The detection can use a real-time algorithm and it can be implemented using recursive methods. The study over this method proved that a comparison of the on-line measured coefficients and the rated values gives the goal of the method, hence, the severity of the fault, and the magnitude of the changes over the system [22].

An important issue is to see the machine as part of a system, not as a simple motion generator. The motion is transmitted to a mechanical drive, like an actuator. Many application that demand high tolerance to faults, include
the coupling between an electrical machine and an actuator. By improving a fault tolerance level also in the actuator, the application receives a high safety in continuous operation. If the motion from the shaft, is split to more moving elements, that are used for the same purpose, the failure of one element is covered by the existence of others [23]. Other actuators can even include machine parts to become moving transmissions [24]. Different structures in this idea can be implemented for outer rotor structures, of brushless machines, or even AC machines.

Nowadays, the tend is to build machines that can offer same services with as simple structures as possible, and lower manufacture costs. In this category will be placed the switched reluctance machine (SRM). From the ordinary SRM to the fault tolerant one, there are steps of changes regarding the inside structure. To be able to build a fault tolerant SRM, first of all, knowledge regarding faults that can occur, and what them influences in the machine’s behavior are, must be studied. By referring strictly to the inside of the machine, only windings can be damaged. The rotor is a passive component, with no fault exposure. As it is known, the reluctance machine is a multi-phase machine, usually with series or parallel connections between the windings. Thus, the faults that can occur are: open circuit usually with series or parallel connections between the windings. The demanded torque. Hence, the drive can also add to the feed of each phase, with respect to the rotor position and the phase currents.

Also, in case of a winding fault it must be able to recognize it, and to recompute the command for the remaining healthy phases. Of course the fault that occurs on one phase will produce a force unbalance that can be observed on the machine’s shaft. To solve this issue, there is an already worked out solution: the closed-loop winding placed on the passive rotor’s poles, presented in [9].

V. A PROPOSAL FOR SWITCHED RELUCTANCE FAULT TOLERANT MACHINE

As an attempt to keep up with the research interest and the demand from the field of industry, this paper presents a proposal for a switched reluctance fault tolerant machine with a novel design. The considered structure for the stator asks for a special design that will use only one winding to create the flux thru two stator poles. In this case the windings are not wound around the poles, like in the case of ordinary SR machine variants, but it is wounded around the yoke, between two stator poles, as it is shown in Fig. 9.

The concept is used generally for the transverse flux machines, and leading from that idea we can input the same winding for the new SR machine. The winding type is presented in [26]. For a set of stator poles an adjacent pair of rotor poles will correspond. Using this structure, the losses in the magnetic circuit will be lower as the flux paths are shorter. The stator outline will have extrusions as pole continuations in order to concentrate the flux and to set "outer slots" for the windings. Multiplication of stator phases and dividing them into channels will increase the fault tolerance due to the independent feed and control on each phase/channel.

The displacement of the phases must consider the force balance on the rotor, and operation in faulty cases. The drive that will control and feed this fault tolerant machine, must use feedback loops to detect the rotor position and the phase currents.

VI. CONCLUSIONS

As artificial intelligence in IT represents a high priority subject, same, in electrical engineering, equipment that can provide wide operation in faulty conditions are required. Engineers working in these fields provided ideas and solutions attempting to conquer higher and higher levels of tolerance for electrical machines and drives. The paper's goal is to underline the most relevant attempts, and gather them in one study. The solution provided by the authors is a beginning in a new challenge to develop a new design for the same purpose, the fault tolerant switched reluctance machine.

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